

Search for contact interactions and large extra dimensions in dilepton events from pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

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A search for nonresonant new phenomena, originating from either contact interactions or large extra spatial dimensions, has been carried out using events with two isolated electrons or muons. These events, produced at the LHC in proton-proton collisions at $\sqrt{s} = 7$ TeV, were recorded by the ATLAS detector. The data sample, collected throughout 2011, corresponds to an integrated luminosity of 4.9 and 5.0 fb⁻¹ in the e^+e^- and $\mu^+\mu^-$ channels, respectively. No significant deviations from the Standard Model expectation are observed. Using a Bayesian approach, 95% confidence level lower limits ranging from 9.0 to 13.9 TeV are placed on the energy scale of $\ell\ell qq$ contact interactions in the left-left isoscalar model. Lower limits ranging from 2.4 to 3.9 TeV are also set on the string scale in large extra dimension models. After combining these limits with results from a similar search in the diphoton channel, slightly more stringent limits are obtained.

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I. INTRODUCTION

Extensions to the Standard Model (SM), such as quark/lepton compositeness and large extra dimensions, predict modifications to the SM dilepton invariant mass spectra. This paper presents a comparison of the number of expected and observed events at high mass in the dielectron and dimuon data sets collected by the ATLAS detector [1] in 2011. These events resulted from proton-proton collisions produced at $\sqrt{s} = 7$ TeV by the LHC [2]. The data are interpreted in the context of contact interactions (CI) and virtual graviton exchange in the Arkani-Hamed–Dimopoulos–Dvali (ADD) model [3].

In the SM, quarks and leptons are fundamental particles. However, if they are composite particles, with at least one common constituent, the interactions of these constituents would manifest themselves through an effective four-fermion contact interaction at energies well below the compositeness scale. This type of contact interaction could also describe a new force with a messenger too heavy for direct observation at the LHC, in analogy with Fermi's nuclear β decay theory [4].

The Lagrangian for a general contact interaction has the form [5]:

$$\begin{aligned} \mathcal{L} = \frac{g^2}{2\Lambda^2} [& \eta_{LL} \bar{\psi}_L \gamma_\mu \psi_L \bar{\psi}_L \gamma^\mu \psi_L \\ & + \eta_{RR} \bar{\psi}_R \gamma_\mu \psi_R \bar{\psi}_R \gamma^\mu \psi_R \\ & + 2\eta_{LR} \bar{\psi}_L \gamma_\mu \psi_L \bar{\psi}_R \gamma^\mu \psi_R], \end{aligned} \quad (1)$$

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where g is a coupling constant chosen so that $g^2/4\pi = 1$; Λ is the contact interaction scale, which, in the context of compositeness models, is the energy scale below which fermion constituents are bound; and $\psi_{L,R}$ are left-handed and right-handed fermion fields, respectively. The parameters η_{ij} , where i and j are L or R (left or right), define the chiral structure of the new interaction. Specific models are constructed by assigning particular combinations of these parameters to be -1 , 0 or $+1$. For example, the left-left isoscalar model (LLIM) is defined by setting $\eta_{LL} = \pm 1$ and $\eta_{RR} = \eta_{LR} = 0$. The LLIM model, commonly used as a benchmark for contact interaction searches [6], is utilized in this analysis.

The addition of the contact interaction Lagrangian to that of the SM modifies the Drell-Yan (DY) production cross section ($q\bar{q} \rightarrow Z/\gamma^* \rightarrow \ell^+\ell^-$). The largest deviations in the dilepton invariant mass spectra, either constructive or destructive, are expected at high mass and are determined by the sign of the parameter η_{ij} and the scale Λ . The differential cross section for the process $q\bar{q} \rightarrow \ell^+\ell^-$, including a contact interaction, can be separated into three components: a SM DY term, a pure contact interaction term (F_C) and a DY-CI interference (F_I) term:

$$\frac{d\sigma}{dm_{\ell\ell}} = \frac{d\sigma_{DY}}{dm_{\ell\ell}} - \eta_{LL} \frac{F_I(m_{\ell\ell})}{\Lambda^2} + \frac{F_C(m_{\ell\ell})}{\Lambda^4}, \quad (2)$$

where $m_{\ell\ell}$ represents the final-state dilepton mass. The full form of this expression is given in Ref. [7]. Constructive (destructive) interference corresponds to $\eta_{LL} = -1$ ($+1$). At the largest Λ values to which this analysis is sensitive, both interference and pure contact interaction terms play significant roles. For example, at dilepton masses greater than 400 GeV and $\Lambda = 12$ TeV, the magnitude of the middle term in Eq. (2), which depends on the interference, is about twice that of the last term.

Nonresonant deviations in the high mass dilepton invariant mass spectra are also predicted in large extra dimension models. These models were introduced to address some of the major unresolved issues in particle physics such as the hierarchy problem. The latter deals with the question of why gravity appears weak in comparison to the other three SM interactions and why the electroweak scale (~ 1 TeV) is 16 orders of magnitude smaller than the Planck scale ($M_{\text{Pl}} \approx 10^{16}$ TeV). Arkani-Hamed, Dimopoulos, and Dvali addressed these issues by postulating the existence of n flat additional spatial dimensions of common size R , compactified on an n -dimensional torus [3]. The fundamental Planck scale in $(4 + n)$ -dimensional spacetime, M_{D} , is then related to the scale M_{Pl} by Gauss's law: $M_{\text{Pl}}^2 = M_{\text{D}}^{n+2} R^n$. Consequently, the hierarchy problem can be solved with a Planck scale resulting from a fundamental scale (M_{D}^{n+2}) near 1 TeV if the volume ($\propto R^n$) is large enough.

In the ADD model, the SM particles and their interactions are confined to a three-dimensional slice of the multi-dimensional world, but gravity permeates the additional dimensions of size R . This results in Kaluza-Klein (KK) modes of the graviton. The mass splitting of these KK modes is determined by the factor $1/R$. Resolution of the hierarchy problem necessitates large extra dimensional volumes and consequently implies small values of $1/R$. This results in an almost continuous spectrum of KK graviton states and hence a nonresonant increase in the expected rate of dilepton events at large invariant mass. Performing the sum over the KK modes in the virtual graviton exchange process leads to an integral which has to be regulated by an ultraviolet cutoff value (Λ_{UV}). The ADD model is a low-energy effective theory valid below the scale of the onset of quantum gravity, characterized by the scale M_{S} . The convention used throughout this analysis is to equate the cutoff to the scale of the effective theory ($\Lambda_{\text{UV}} = M_{\text{S}}$).

For virtual graviton exchange, it is standard practice to present limits on the size of the extra dimensions in terms of M_{S} , taken to be the string scale, which is related to M_{D} by the following expression [8]:

$$M_{\text{S}} = 2\sqrt{\pi} \left[\Gamma\left(\frac{n}{2}\right) \right]^{1/(n+2)} M_{\text{D}}. \quad (3)$$

The strength of gravity in the presence of extra dimensions is typically parametrized by $\eta_{\text{G}} = \mathcal{F}/M_{\text{S}}^4$, where \mathcal{F} is a dimensionless parameter of order unity. The definition of \mathcal{F} depends on the formalism chosen [8], with three popular conventions: Giudice-Rattazzi-Wells (GRW) [9], Hewett [10] and Han-Lykken-Zhang (HLZ) [11]. The different values are

$$\begin{aligned} \mathcal{F} &= 1 \text{ (GRW)}, & \mathcal{F} &= \frac{2\lambda}{\pi} = \frac{\pm 2}{\pi} \text{ (Hewett)}, \\ \mathcal{F} &= \frac{2}{n-2} \text{ for } n > 2 \text{ (HLZ)}. \end{aligned} \quad (4)$$

In the GRW and HLZ representations, gravitational effects interfere constructively with the SM processes, while in Hewett's convention there can be destructive or constructive interference. This is encapsulated in the parameter λ , which is equal to $+1$ (-1) for constructive (destructive) interference.

The total cross section (σ_{tot}), including effects of $q\bar{q}$ - and gg -initiated virtual graviton exchange, may be parametrized as

$$\sigma_{\text{tot}} = \sigma_{\text{SM}} + \eta_{\text{G}} F_{\text{int}} + \eta_{\text{G}}^2 F_{\text{G}}, \quad (5)$$

where σ_{SM} is the SM cross section for the process being considered, and F_{int} and F_{G} are functions of the cross sections involving the interference and pure graviton effects, respectively. Note that the interference term has a linear dependence on η_{G} , and therefore a quartic dependence on M_{S} (i.e., $\eta_{\text{G}} \propto 1/M_{\text{S}}^4$), whereas the pure graviton exchange term is quadratic in η_{G} and therefore has a $1/M_{\text{S}}^8$ dependence. A study of signal yields in the kinematic range relevant to this analysis shows that the pure graviton term dominates those yields. This is in part due to the fact that the gg -initiated contribution to the graviton exchange process does not interfere with the $q\bar{q}$ -initiated DY process. Results are nevertheless presented for both $1/M_{\text{S}}^4$ and $1/M_{\text{S}}^8$ priors.

Previous searches for contact interactions have been carried out in neutrino-nucleus and electron-electron scattering [12,13], as well as at electron-positron [14–18], electron-proton [19,20], and hadron colliders [21–28]. In the case of $eeqq$ contact interactions, the limits in the LLIM for all quark flavors from e^+e^- experiments are $\Lambda^- > 7.2$ TeV and $\Lambda^+ > 12.9$ TeV [14] at 95% confidence level (C.L.) for $\eta_{\text{LL}} = -1$ and $+1$, respectively. These limits assume that contact interactions of electrons with all quark flavors are of the same strength. The best limits set in the specific case of first generation quarks are $\Lambda^- > 9.1$ TeV and $\Lambda^+ > 8.6$ TeV [18] at 95% C.L. In the case of $eeqq$ contact interactions, the best limit for constructive interference is $\Lambda^- > 10.1$ TeV from the ATLAS analysis of the first 1 fb^{-1} of 2011 data [28]. The best limits in the case of $\mu\mu qq$ contact interactions are from an analysis of the same data: $\Lambda^- > 8.0$ TeV and $\Lambda^+ > 7.0$ TeV [28].

Previous searches for large extra dimensions in the ADD model via virtual graviton exchange have been performed at electron-positron [29–34], electron-proton [20,35], and hadron colliders [25,36–42]. Presently, the most stringent mass limits in the dielectron and dimuon channels require $M_{\text{S}} > 2.8$ TeV for each channel and 3.1 TeV when combined (in the GRW formalism with no K factor) [38]. The best limits to date arise from the combination of these dilepton results with those from a search in the diphoton final state, which increases the limit by ~ 0.1 TeV [38]. The following sections describe the first virtual graviton exchange search performed by ATLAS using dilepton data and its combination with an ATLAS diphoton data search [42].

II. ATLAS DETECTOR

ATLAS is a multipurpose particle detector composed of three main subsystems: the inner tracking detector, the calorimeter system and the muon spectrometer. The inner detector is used to track charged particles within a pseudorapidity η^1 in the range $|\eta| < 2.5$. It comprises a silicon pixel detector, a silicon-strip tracker and a transition radiation tracker. An axial 2 T magnetic field is produced by a superconducting solenoid.

The calorimeter system, covering $|\eta| < 4.9$, surrounds the solenoid and provides three-dimensional reconstruction of electromagnetic and hadronic showers. The lead/liquid-argon electromagnetic sampling calorimeter covers $|\eta| < 2.5$ and is finely segmented with a readout granularity varying by layer and with cells as small as 0.025×0.025 in (η, ϕ) to provide precise energy and position resolution, as needed for electron and photon identification and energy measurement. Hadron calorimetry is provided by an iron/scintillator tile calorimeter in the central pseudorapidity range $|\eta| < 1.7$ and a lead/liquid-argon calorimeter extending the pseudorapidity range up to $|\eta| = 3.2$. Both the electromagnetic and hadronic calorimeters have liquid-argon-based forward detectors, with copper or tungsten as an absorber, to extend coverage up to $|\eta| = 4.9$.

Outermost is the muon spectrometer, another key detector component for this analysis. Three layers of precision tracking chambers, comprising monitored drift tubes and cathode strip chambers, enable muon reconstruction up to $|\eta| = 2.7$. The magnetic field is provided by three large air-core toroidal magnet systems (one barrel and two end caps), each consisting of eight azimuthally symmetric superconducting coils. Triggering capability up to $|\eta| = 2.4$ is provided by fast resistive plate chambers in the barrel and thin-gap chambers in the end caps.

III. SIGNAL AND BACKGROUND MODELING

The dominant background contribution comes from the SM DY process with smaller contributions from $t\bar{t}$ and electroweak diboson (WW , WZ , and ZZ) production. In the dielectron channel, there is also a significant background from multijet and W + jets events in which jets are misidentified as electrons. Backgrounds are estimated using fully simulated Monte Carlo (MC) samples except for the combined multijet and W + jets background, which is determined from the data.

¹ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis along the beam pipe. The x axis points from the IP to the center of the LHC ring, and the y axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$.

DY samples are generated with PYTHIA 6.421 [43] using MRST2007 LO** parton distribution functions (PDFs) [44]. The diboson background is generated with HERWIG 6.510 [45] using MRST2007 LO** PDFs. For the $t\bar{t}$ background, event generation is performed with MC@NLO 4.01 [46] and the CTEQ 6.6 PDFs [47], as well as HERWIG to model the underlying event and parton showers. Production of diboson and $t\bar{t}$ events relies on JIMMY 4.31 [48] to describe multiple interactions.

For the contact interactions analysis, PYTHIA 6.421 and the MRST2007 LO** PDFs are used to generate both DY and CI as part of the same process in order to properly handle the interference between DY and CI contributions, as shown in Eq. (2). All quark flavors contribute to the DY + CI production.

Final-state radiation is simulated with PHOTOS [49] for all the samples listed above. Higher-order QCD corrections are implemented via mass-dependent K factors defined as the ratio of the next-to-next-to-leading-order (NNLO) Z/γ^* cross section calculated using PHOZPR [50] and the MSTW2008 NNLO PDFs [51], to the LO Z/γ^* cross section from PYTHIA. Higher-order electroweak corrections originating from virtual gauge-boson loops are computed using the HORACE NLO event generator [52]. The mass-dependent QCD and electroweak K factors are applied to both DY and DY + CI samples.

For the large extra dimensions analysis, SHERPA 1.3.1 [53] and the CTEQ6L PDFs [54] are used to generate DY + ADD events at leading order. The generated dilepton mass is required to be less than the scale M_S , which is chosen to be in the range between 2 and 3 TeV in this study, since the model is not valid at energies beyond that scale.

Finally, the generated samples are processed through a full simulation of the ATLAS detector [55] based on GEANT 4 [56] and reconstructed with the same software as for the data. Several corrections derived from data control samples are applied to the simulated samples. Specifically, the energy scale and resolution for electrons are corrected so that the $Z \rightarrow ee$ mass distribution in simulation matches the data [57]. Similarly, the muon transverse momentum scale and resolution are adjusted to reproduce the muon tracking performance measured in $Z \rightarrow \mu\mu$ data as well as several dedicated data samples [58]. The effect of pileup (multiple pp interactions in the same or nearby bunch crossings) is included by superimposing minimum bias events, in the same proportion as in data, on top of the hard scattering process generated. Small corrections are included in the analysis to properly describe the pileup conditions for the selected data sample.

IV. EVENT SELECTION AND COMPARISON BETWEEN EXPECTED AND OBSERVED YIELDS

This analysis follows the same event selection as the search for new heavy resonances [59] in the dielectron

channel but uses a somewhat tighter selection in the dimuon channel.

The data sample was collected during LHC operation in 2011 and corresponds to a total integrated luminosity of 4.9 and 5.0 fb⁻¹ in the e^+e^- and $\mu^+\mu^-$ final states, respectively. The events recorded by the ATLAS detector were selected by requiring that they pass specific triggers. The trigger for the dielectron data set required the presence of two electromagnetic clusters consistent with originating from electrons with transverse momentum p_T above 20 GeV, whereas events in the muon data set were required to pass at least one of two single-muon triggers with p_T thresholds of 22 GeV and 40 GeV.

After passing the trigger selection, events are required to have a pair of either electrons or muons with p_T greater than 25 GeV. Furthermore, events are required to be recorded during stable beam conditions and with detector components operational. To reject cosmic ray events and beam halo background, events are required to have a reconstructed vertex with at least three charged particle tracks with $p_T > 0.4$ GeV. If more than one such vertex is found, the vertex with the largest Σp_T^2 is selected as the primary vertex of the event, where the sum is over all charged particles associated with the given vertex. Electron candidates are confined to $|\eta| < 2.47$, with the calorimeter barrel-to-end-cap transition region $1.37 \leq |\eta| \leq 1.52$ excluded due to the degraded energy resolution in this region. No explicit η requirement is placed on muon candidates, but the selection described below leads to negligible acceptance beyond $|\eta|$ of approximately 2.5.

Electron candidates are formed from clusters of cells in the electromagnetic calorimeter where energy is deposited. Identification criteria based on the transverse shower shape, the leakage into the hadronic calorimeter, and the association to an inner detector track are applied to the cluster to satisfy the *medium* electron definition [57]. The electron energy is obtained from the calorimeter measurements and its direction from the associated inner detector track. A hit in the first layer of the pixel detector is required (if an active pixel module is traversed) to suppress background from photon conversions. Further jet background suppression is achieved by demanding that the highest- p_T electron in the event be isolated. To this effect, the sum of the transverse energies, ΣE_T , in calorimeter cells within a radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ of 0.2 around the electron direction, is required to be less than 7 GeV. The core of the electron energy deposition is excluded and the sum is corrected for transverse shower leakage and pileup. The two electron candidates are not required to have opposite charge because of possible charge misidentification either due to bremsstrahlung or limited momentum resolution of the inner detector at high p_T . If the event contains more than two selected electrons, the two electrons with the highest- p_T sum are chosen. For these selection criteria, the overall event acceptance for DY events has a small dependence on the

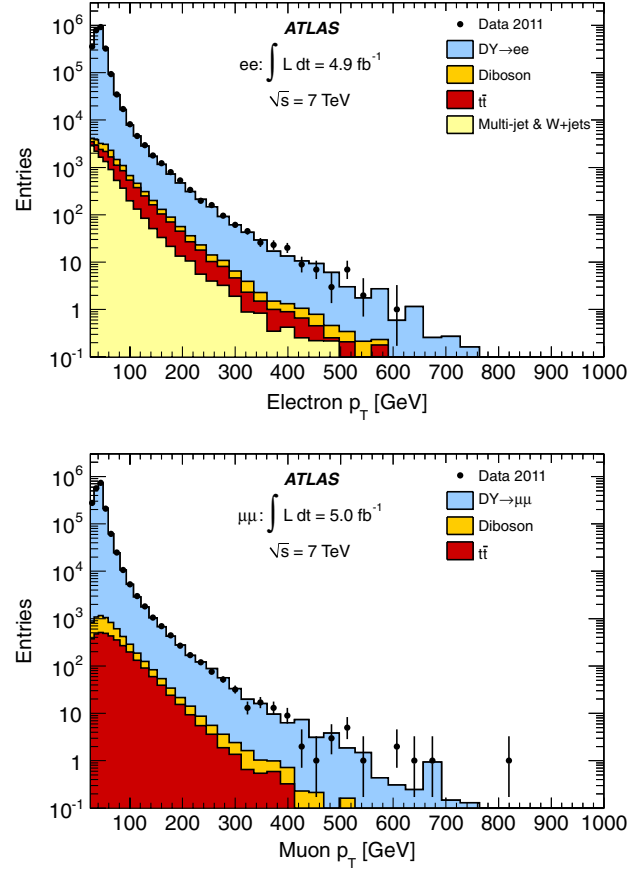


FIG. 1 (color online). Lepton transverse momentum distributions in the dielectron (top panel) and dimuon (bottom panel) channels for data (points) and Monte Carlo simulation (histograms). The bin width is constant in $\log(p_T)$.

dielectron mass above 500 GeV, with a value of approximately 65% at 1 TeV.

Muon candidates are reconstructed independently in the inner detector and the muon spectrometer. The momentum is taken from a combined fit to the measurements from the two subsystems. To obtain optimal momentum resolution and accurate modeling by the simulation, muon candidates are required to have at least three hits in each of the inner, middle, and outer detector layers of the muon spectrometer, and to have at least one hit in each of two different layers in the nonbending xy plane. To suppress background from cosmic rays, requirements are imposed on the primary vertex (PV) position and the muon impact parameter relative to the PV: z coordinate of the PV $|z_{PV}| < 200$ mm, muon transverse impact parameter $|d_0| < 0.2$ mm and muon z coordinate $|z_0 - z_{PV}| < 1$ mm. Furthermore, the muons are required to be isolated to reduce background from jets: $\Sigma p_T(R < 0.3)/p_T(\mu) < 0.05$, where the sum is over inner detector tracks within a radius of 0.3 around the muon direction. If more than one opposite-sign muon pair is found in an event, the pair with the highest- p_T sum is chosen. The overall event acceptance for DY events has only a weak dependence on the dimuon mass, with a value of approximately 40% at 1 TeV.

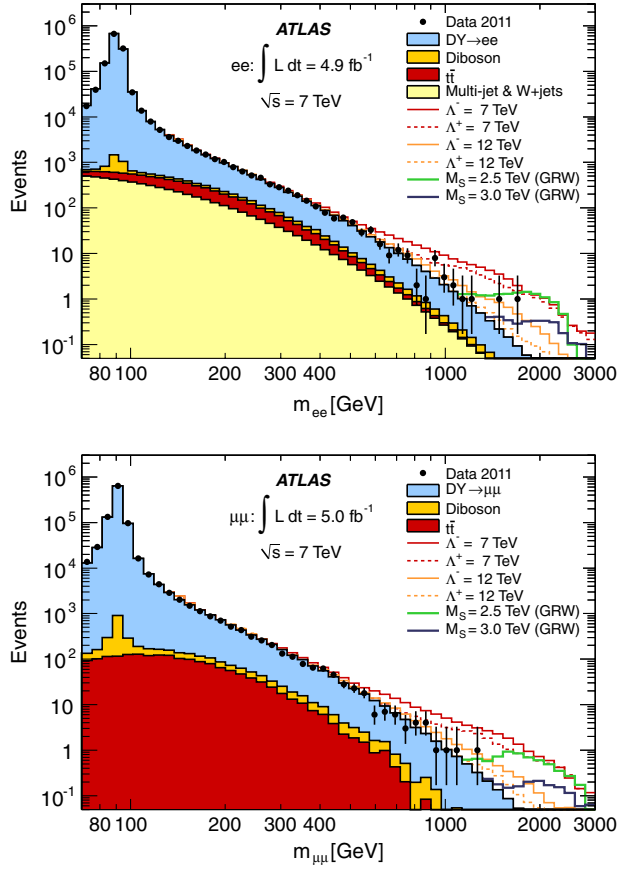


FIG. 2 (color online). Dielectron (top panel) and dimuon (bottom panel) invariant mass distributions for data (points) and Monte Carlo simulation (filled histograms). The open histograms correspond to the distributions expected in the presence of contact interactions or large extra dimensions for several model parameters. The bin width is constant in $\log(m_{\ell\ell})$.

This is lower than the acceptance in the dielectron channel primarily due to the stringent requirements on the presence of hits in all three layers of the muon spectrometer and the extent of the three-layer geometrical coverage.

The $W + \text{jets}$ background in the dimuon channel is estimated from simulated samples and is found to be negligible since the event must contain two well-measured high- p_T isolated muons. Likewise, the multijet background, estimated directly from the data by reversing the muon isolation criterion, is found to be negligible. The multijet and $W + \text{jets}$ backgrounds are not negligible in the dielectron channel. They are estimated primarily from the data using several methods [59]. The first method determines the multijet background from the data and relies on the MC simulation for the $W + \text{jets}$ contribution. The background is measured with a template built by reversing one of the electron identification criteria and normalized to data in the range $70 < m_{ee} < 200$ GeV. Another independent method that is sensitive to both multijet and $W + \text{jets}$ backgrounds uses jet-enriched data samples either from jet triggers or from the same trigger used to select the events in this analysis. The method relies on

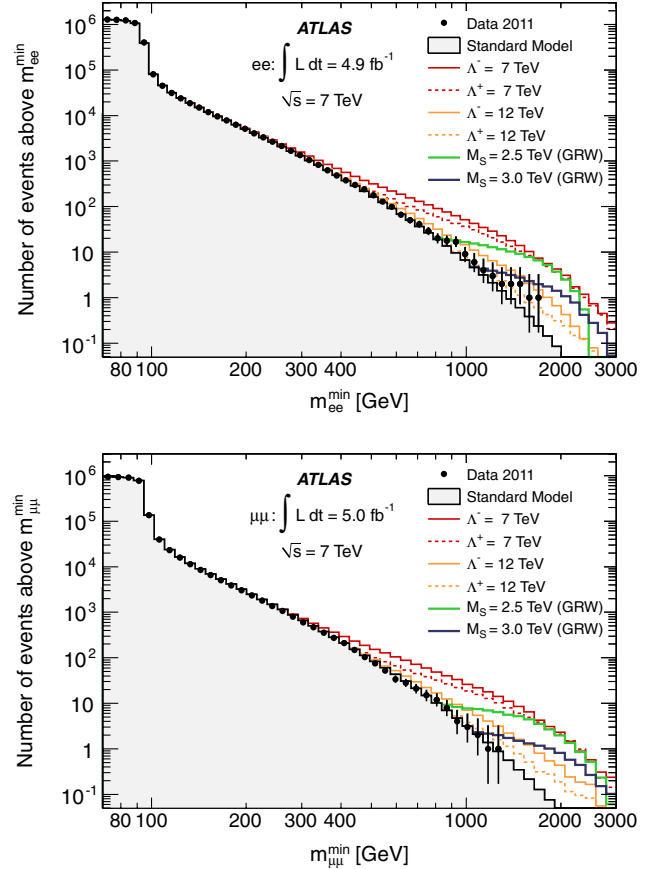


FIG. 3 (color online). Distribution of the number of events with dilepton mass above $m_{\ell\ell}^{\min}$ for data (points) and SM prediction from Monte Carlo simulation (filled histograms, shaded gray) in the dielectron channel (top panel) and dimuon channel (bottom panel). The open solid and dashed histograms correspond to the expected distributions in the presence of contact interactions or large extra dimensions for several model parameters. The bin width is constant in $\log(m_{\ell\ell}^{\min})$.

jet misidentification rates, defined as the number of jets that pass the full electron selection divided by the number that pass a loose electron selection obtained by reversing one of the identification criteria. The background estimate is then constrained by a fit in the range $140 < m_{ee} < 850$ GeV. The final combined multijet and $W + \text{jets}$ background is obtained with a simple average of the expected event yields from the different methods.

Extensive comparisons between data and MC simulation were performed at the level of single-lepton distributions to confirm that the simulation reproduces the selected data, especially at high momentum. Figure 1 shows good data-MC agreement in the lepton transverse momentum distributions for events passing all selection criteria.

Figure 2 shows the dielectron and dimuon mass distributions for selected events. Also shown are the predicted contributions from SM and new phenomena (NP) for several choices of model parameters. The expected SM distribution is dominated by the DY process over the

TABLE I. Expected and observed numbers of events in the dielectron channel for the contact interactions search region. The yields are normalized to the Z peak control region and include predictions for SM backgrounds as well as for SM + CI with different CI scales for constructive (Λ^-) and destructive (Λ^+) interference. The errors quoted originate from both systematic uncertainties and limited MC statistics.

m_{ee} (GeV)	400–550	550–800	800–1200	1200–1800	>1800
DY	203 ± 10	62.5 ± 3.4	12.1 ± 0.9	1.38 ± 0.17	0.085 ± 0.025
$t\bar{t}$	22.6 ± 2.1	4.05 ± 0.34	0.308 ± 0.026	<0.05	<0.01
Diboson	12.1 ± 0.7	4.08 ± 0.21	0.88 ± 0.05	0.111 ± 0.006	0.0100 ± 0.0006
Multijet/ W + jets	38 ± 23	11 ± 8	2.0 ± 1.8	0.24 ± 0.28	0.022 ± 0.029
Total background	276 ± 25	82 ± 9	15.3 ± 2.0	1.74 ± 0.33	0.12 ± 0.04
$\Lambda^- = 3$ TeV	1460 ± 70	1400 ± 80	1090 ± 60	525 ± 35	148 ± 13
$\Lambda^- = 4$ TeV	680 ± 40	519 ± 27	360 ± 21	171 ± 12	44 ± 4
$\Lambda^- = 5$ TeV	463 ± 30	281 ± 15	162 ± 9	77 ± 5	19.8 ± 1.9
$\Lambda^- = 7$ TeV	332 ± 27	145 ± 10	59 ± 4	22.0 ± 1.6	4.8 ± 0.5
$\Lambda^- = 12$ TeV	293 ± 27	96 ± 9	23.6 ± 2.3	5.1 ± 0.5	0.87 ± 0.14
$\Lambda^+ = 3$ TeV	1080 ± 50	1120 ± 60	920 ± 50	493 ± 33	128 ± 11
$\Lambda^+ = 4$ TeV	484 ± 30	373 ± 20	291 ± 17	156 ± 10	40 ± 4
$\Lambda^+ = 5$ TeV	342 ± 27	182 ± 11	114 ± 6	61 ± 4	18.3 ± 1.6
$\Lambda^+ = 7$ TeV	268 ± 27	102 ± 10	37.4 ± 2.6	15.1 ± 1.0	4.3 ± 0.4
$\Lambda^+ = 12$ TeV	260 ± 27	82 ± 9	15.1 ± 2.2	2.5 ± 0.4	0.41 ± 0.08
Data	270	88	17	3	0

entire mass range and is found to describe the data well. The level of agreement with the SM expectation is also illustrated in Fig. 3, which shows the number of events above a minimum mass $m_{\ell\ell}^{\min}$.

A more quantitative comparison is provided in Tables I and II showing the numbers of observed and expected

events in the dielectron and dimuon channels, respectively. The expected yields are normalized to the number of events observed in the Z peak control region ($70 < m_{\ell\ell} < 110$ GeV). The mass region shown in these tables corresponds to the CI search region defined by $m_{\ell\ell} > 400$ GeV. These tables also display the expected

TABLE II. Expected and observed numbers of events in the dimuon channel for the contact interactions search region. The yields are normalized to the Z peak control region and include predictions for SM backgrounds as well as for SM + CI with different CI scales for constructive (Λ^-) and destructive (Λ^+) interference. The errors quoted originate from both systematic uncertainties and limited MC statistics.

$m_{\mu\mu}$ (GeV)	400–550	550–800	800–1200	1200–1800	>1800
DY	123 ± 6	37.4 ± 2.2	7.1 ± 0.6	0.82 ± 0.11	0.058 ± 0.022
$t\bar{t}$	13.4 ± 1.4	3.1 ± 0.5	0.04 ± 0.12	<0.05	<0.01
Diboson	7.9 ± 0.4	2.66 ± 0.15	0.55 ± 0.04	0.075 ± 0.006	0.0124 ± 0.0031
Total background	145 ± 6	43.2 ± 2.2	7.7 ± 0.6	0.89 ± 0.11	0.070 ± 0.022
$\Lambda^- = 3$ TeV	870 ± 50	770 ± 50	580 ± 40	296 ± 28	82 ± 22
$\Lambda^- = 4$ TeV	405 ± 19	301 ± 17	201 ± 14	87 ± 8	27 ± 7
$\Lambda^- = 5$ TeV	256 ± 12	159 ± 8	94 ± 6	41 ± 4	12.7 ± 3.4
$\Lambda^- = 7$ TeV	184 ± 9	79 ± 4	30.1 ± 1.9	12.3 ± 1.2	2.9 ± 0.8
$\Lambda^- = 12$ TeV	157 ± 9	50.6 ± 3.1	12.3 ± 0.9	2.81 ± 0.31	0.53 ± 0.15
$\Lambda^+ = 3$ TeV	628 ± 31	650 ± 40	500 ± 40	248 ± 23	75 ± 20
$\Lambda^+ = 4$ TeV	271 ± 12	203 ± 11	159 ± 11	85 ± 8	22 ± 6
$\Lambda^+ = 5$ TeV	182 ± 9	98 ± 5	64 ± 4	31.4 ± 2.9	11.5 ± 3.0
$\Lambda^+ = 7$ TeV	141 ± 8	50.8 ± 3.1	19.7 ± 1.2	8.4 ± 0.8	2.5 ± 0.7
$\Lambda^+ = 12$ TeV	140 ± 8	40.2 ± 3.0	7.4 ± 0.7	1.57 ± 0.20	0.25 ± 0.08
Data	151	36	9	1	0

yields for the SM + CI signal for the two scenarios where the CI interferes either constructively or destructively with the SM.

V. SYSTEMATIC UNCERTAINTIES

Except for the multijet and $W + \text{jets}$ background contributions to the dielectron channel, all signal and background event yield estimates are based on MC simulation. Because these yields are normalized in the Z peak control region, only mass-dependent systematic uncertainties affect the event yield estimates in the higher-mass signal region. The only exception is a 5% uncertainty applied to the signal yield to account for the uncertainty in the Z/γ^* cross section which affects the signal normalization.

Experimental uncertainties arise from lepton energy/momentum scale and resolution, as well as trigger, reconstruction and identification efficiencies. In the dielectron channel, the largest experimental uncertainty comes from the combined multijet and $W + \text{jets}$ background estimate. It is determined from the envelope of the three separate methods used, including the effect of varying the mass ranges in the background fits and the uncertainties in the η and p_T dependence of the jet misidentification rates. Electron energy scale and resolution are determined from data via $J/\psi \rightarrow ee$ and $Z \rightarrow ee$ mass distributions, as well as studies of electron E/p in $W \rightarrow e\nu$ decays [57]. The uncertainty in the constant term that dominates the resolution at high energy has negligible impact on this analysis. A somewhat larger impact comes from the energy scale knowledge, resulting in a systematic error of 1.2% and 2.4% for dielectron masses of 1 and 2 TeV, respectively. A slight efficiency drop of 1.0% per TeV is predicted by the simulation due to the isolation requirement on the leading electron. To account for this effect, an uncertainty of the same magnitude is introduced.

In the dimuon channel, the largest contribution to the experimental systematic error comes from the muon reconstruction efficiency and muon resolution. A slight drop in reconstruction efficiency is predicted by the simulation at high p_T due to the presence of additional hits in the muon spectrometer from muons undergoing large energy loss in

the detector. An uncertainty of 3.0% (6.0%) at a dimuon mass of 1 (2) TeV is assessed, corresponding to the magnitude of this effect. The limited knowledge of the momentum scale determined from $Z \rightarrow \mu\mu$ data has a negligible impact on the analysis. The momentum resolution in the simulation is adjusted based on $Z \rightarrow \mu\mu$ and $W \rightarrow \mu\nu$ data, as well as dedicated straight muon track data collected with the toroids turned off and tracks passing through overlapping sectors in the muon spectrometer. The latter provide two independent momentum measurements for the same muon. The toroid-off and overlapping sector tracks are key to determining the muon reconstruction performance at high p_T . The uncertainty in the muon resolution, taken as equal in magnitude to the correction applied to the simulation, results in a change in the event yield of 1.2% (12%) for $m_{\mu\mu} = 1$ (2) TeV.

The largest error contribution due to theory arises from limited knowledge of the PDFs, α_S , and QCD K factors. Scale uncertainties are computed by taking the maximum deviations obtained by independently varying the renormalization (μ_R) and factorization (μ_F) scales by a factor of 2 but with the constraint that the ratio μ_F/μ_R does not change by more than a factor of 2. The α_S and PDF uncertainties are determined with the MSTW2008NNLO eigenvector PDF sets and the different PDFs corresponding to variations of α_S . The overall uncertainty is computed using 90% confidence level ranges and includes the envelope of the uncertainty bands for the following different PDF sets: MSTW2008, NNPDF2.1, CT10, and CT10W. PDFs are the largest source of uncertainty, with the envelope of all PDFs considered becoming the dominant contribution above a few hundred GeV. Uncertainties in the electroweak K factor [60] originate from the calculation of real boson radiation, $\mathcal{O}(\alpha\alpha_S)$ corrections, higher-order electroweak corrections, an assumed uncertainty of 10% in the contribution from photon-induced processes, and a difference in the electroweak renormalization scheme definition used in PYTHIA and in the calculation of the electroweak corrections with HORACE. The latter source is the largest contribution to the electroweak uncertainty.

The systematic uncertainties are summarized in Table III. Although not explicitly listed in this table, the uncertainty

TABLE III. Summary of systematic uncertainties in the expected numbers of events for a dilepton mass of 1 TeV (2 TeV). NA indicates that the uncertainty is not applicable.

Source	ee		$\mu\mu$	
	Signal	Background	Signal	Background
Normalization	5% (5%)	NA	5% (5%)	NA
PDFs/ α_S /scale	NA	7% (20%)	NA	7% (20%)
Electroweak K factor	NA	2.3% (4.5%)	NA	2.3% (4.5%)
Efficiency	1.0% (2.0%)	1.0% (2.0%)	3.0% (6.0%)	3.0% (6.0%)
Scale/Resolution	1.2% (2.4%)	1.2% (2.4%)	1.2% (12%)	1.2% (12%)
Multijet/ $W + \text{jets}$ background	NA	12% (26%)	NA	<0.1%
Total	5% (6%)	14% (33%)	6% (14%)	8% (25%)

due to limited MC statistics is also taken into account in the limit setting. For DY + CI MC samples, this uncertainty grows from about 4% at low $m_{\ell\ell}$ to about 30% at high $m_{\ell\ell}$ for $\Lambda = 12$ TeV.

VI. STATISTICAL ANALYSIS

The data analysis proceeds with a Bayesian method to compare the observed event yields with the expected yields for a range of different NP model parameters (where the NP corresponds to either contact interactions or large extra dimensions). Specifically, the number of expected events in a given search region is

$$\mu = n_{\text{DY+NP}}(\theta, \bar{\nu}) + n_{\text{non-DY bg}}(\bar{\nu}), \quad (6)$$

where $n_{\text{DY+NP}}(\theta, \bar{\nu})$ is the number of events predicted by the DY + NP simulation for a particular choice of NP model parameter θ , $n_{\text{non-DY bg}}(\bar{\nu})$ is the number of non-DY background events, and $\bar{\nu}$ represents the set of Gaussian nuisance parameters that account for systematic uncertainties. The parameter θ corresponds to a choice of energy scale Λ and interference parameter η_{LL} in the CI analysis or to a choice of string scale M_S and formalism in the ADD analysis. In the case of the CI analysis, the input to evaluate the complete set of μ values is shown in Tables I and II for the dielectron and dimuon channels, respectively. For each mass bin, a second-order polynomial is used to model the dependence of μ on $1/\Lambda^2$. In the case of the ADD analysis, μ is also parametrized by a second-order polynomial but as a function of $1/M_S^4$.

The likelihood of observing a set of \bar{n} events in N invariant mass bins is given by a product of Poisson probabilities for each mass bin k :

$$\mathcal{L}(\bar{n} | \theta, \bar{\nu}) = \prod_{k=1}^N \frac{\mu_k^{n_k} e^{-\mu_k}}{n_k!}. \quad (7)$$

According to Bayes' theorem, the posterior probability for the parameter θ given \bar{n} observed events is

$$\mathcal{P}(\theta | \bar{n}) = \frac{1}{Z} \mathcal{L}_M(\bar{n} | \theta) P(\theta), \quad (8)$$

where Z is a normalization constant and the marginalized likelihood \mathcal{L}_M corresponds to the likelihood after all nuisance parameters have been integrated out. This integration is performed assuming that the nuisance parameters are correlated across all mass bins; Table III shows which parameters are taken into account for either or both of the signal and background expectations. The prior probability $P(\theta)$ is chosen to be flat in either $1/\Lambda^2$ or $1/\Lambda^4$ for the CI analysis, and either $1/M_S^4$ or $1/M_S^8$ for the ADD analysis. These choices are motivated by the form of Eqs. (2) and (5). The 95% C.L. limit is then obtained by finding the value θ_{lim} satisfying $\int_0^{\theta_{\text{lim}}} \mathcal{P}(\theta | \bar{n}) d\theta = 0.95$, where θ is chosen to be $1/\Lambda^2$, $1/\Lambda^4$, $1/M_S^4$ or $1/M_S^8$. The above calculations have been performed with the Bayesian Analysis Toolkit

(BAT) [61], which uses a Markov chain Monte Carlo technique to integrate over nuisance parameters.

VII. CONTACT INTERACTIONS ANALYSIS AND RESULTS

To test the consistency between the data and the SM in the CI search region ($m_{\ell\ell} > 400$ GeV), a likelihood ratio test is performed by producing a set of SM-like pseudoexperiments and comparing the likelihood ratio between the signal + background and pure background hypotheses obtained in the data to the results of the pseudoexperiments. The signal + background likelihood is evaluated at the Λ value that maximizes it. The derived p value, corresponding to the probability of observing a fluctuation in the pseudoexperiments that is at least as signal-like as that seen in the data (i.e., with a maximum likelihood ratio greater than or equal to that obtained in the data), is estimated to be 15% (76%) in the dielectron channel and 79% (59%) in the dimuon channel for constructive (destructive) interference. These values indicate that there is no significant evidence for contact interactions in the analyzed data, and thus limits are set on the contact interaction scale Λ .

Limits are obtained with the Bayesian method described above. Electroweak corrections are applied to both DY and DY + CI samples for consistency, although part of the electroweak corrections cannot be computed reliably due to the unknown new phenomena represented by the contact interaction. This particular choice results in slightly more conservative limits.

The expected 95% C.L. lower limit values on the energy scale Λ are found to be 13.8 ± 1.7 TeV for constructive interference (Λ^-) and 10.4 ± 1.0 TeV for destructive interference (Λ^+) in the dielectron channel. The corresponding expected limits in the dimuon channel are 12.7 ± 1.5 TeV and 9.9 ± 1.1 TeV. The quoted uncertainties correspond to the 68% range of limits surrounding the median value (taken to be the expected limit) of all limits obtained with a set of pseudoexperiments. Limits are expected to be stronger in the dielectron channel than in the dimuon channel due to the significantly larger acceptance for the dielectron selection.

The observed limits (at 95% C.L.) are $\Lambda^- > 12.1$ TeV and $\Lambda^+ > 9.5$ TeV in the dielectron channel for constructive and destructive interference, respectively. The corresponding limits in the dimuon channel are $\Lambda^- > 12.9$ TeV and $\Lambda^+ > 9.6$ TeV. These limits are summarized in Table IV.

If instead of choosing the prior to be flat in $1/\Lambda^2$, it is selected to be flat in $1/\Lambda^4$ to match the form of the pure CI term in Eq. (2), the observed limit in the dielectron channel becomes weaker by 0.7 TeV for constructive interference and 0.4 TeV for destructive interference. The corresponding respective shifts to lower values are 1.2 and 0.6 TeV in the dimuon channel; see Table IV.

Finally, a limit is set for the combination of the dielectron and dimuon channels, assuming lepton universality, by

TABLE IV. Expected and observed 95% C.L. lower limits on the contact interaction energy scale Λ for the dielectron and dimuon channels, as well as for the combination of those channels. Results are provided for constructive and destructive interference as well as different choices of flat priors: $1/\Lambda^2$ and $1/\Lambda^4$.

Channel	Prior	Expected limit (TeV)		Observed limit (TeV)	
		Constructive	Destructive	Constructive	Destructive
ee	$1/\Lambda^2$	13.8	10.4	12.1	9.5
	$1/\Lambda^4$	12.5	9.8	11.4	9.1
$\mu\mu$	$1/\Lambda^2$	12.7	9.9	12.9	9.6
	$1/\Lambda^4$	11.6	9.1	11.7	9.0
$ee + \mu\mu$	$1/\Lambda^2$	15.0	11.3	13.9	10.2
	$1/\Lambda^4$	13.8	10.5	12.9	9.8

computing a combined posterior probability for the two channels. The following sources of systematic uncertainty are treated as fully correlated between the two channels: PDF and α_S , QCD and electroweak K factors, and Z/γ^* cross section for normalization. All other sources are treated as uncorrelated. The resulting combined limits are $\Lambda^- > 13.9$ TeV and $\Lambda^+ > 10.2$ TeV for the $1/\Lambda^2$ prior. Table IV summarizes all limits for the two priors considered in this analysis.

VIII. LARGE EXTRA DIMENSIONS ANALYSIS AND RESULTS

The search for large extra dimensions is carried out similarly to that for contact interactions. A difference from the CI analysis is that the DY component present in the SHERPA DY + ADD simulated samples is subtracted out to compute the net ADD contribution to the total event yield. The DY background is modeled with the same PYTHIA DY sample as is used for the CI analysis. Another difference is that the search is performed in only one mass bin with the minimum mass chosen at the value giving the strongest expected limit. This optimization results in a signal region with a minimum mass requirement of 1300 GeV as determined from a set of pseudoexperiments in each of the dielectron and dimuon channels. Table V presents the expected and observed event yields in the signal region, including the expectation for several M_S values in the GRW formalism.

The consistency between the number of observed events in the data and the predicted SM contribution is assessed using a set of SM-like pseudoexperiments. Using the same likelihood ratio approach as for the CI analysis, p values of 6% and 68% are obtained in the dielectron and dimuon channels, respectively. These values indicate that there is no significant evidence for large extra dimensions, and thus limits are set on the scale M_S . The observed limits are $M_S > 2.73$ (2.62) TeV in the dielectron channel and $M_S > 2.83$ (2.61) TeV in the dimuon channel at 95% C.L. with a prior flat in $1/M_S^4$ ($1/M_S^8$). Table VI shows these observed limits along with the expected limits. Limits in the dielectron channel are slightly worse than expected due to the larger number of events observed

in the data compared with the SM expectation. The dielectron and dimuon channels are combined taking correlated systematic uncertainties into account in a way identical to the CI analysis.

A search for large extra dimensions has also been carried out in the diphoton final state using the data sample collected by ATLAS in 2011 [42]. The results of that search are combined with the dilepton results presented here with the use of BAT. Correlated sources of systematic uncertainty are treated as follows. The PDF uncertainty in the SM diphoton and DY production is considered to be fully correlated between the ee , $\mu\mu$ and $\gamma\gamma$ channels, whereas the multijet background uncertainty is fully correlated between the ee and $\gamma\gamma$ final states. It should be noted that the ee and $\gamma\gamma$ samples are statistically uncorrelated since ee candidates have been explicitly removed from the diphoton analysis at the event selection stage. The observed and expected combined limits are given in Table VI, with the most stringent observed limit obtained for the dilepton-diphoton combination: $M_S > 3.22$ (3.12) TeV with a prior flat in $1/M_S^4$ ($1/M_S^8$) in the GRW formalism.

TABLE V. Expected and observed number of events with $m_{\ell\ell} > 1300$ GeV in the dielectron and dimuon channels. Yields given for different M_S values correspond to the sum of signal and background events, with the signal obtained in the GRW formalism. All yields are normalized to the Z peak control region. The errors quoted originate from systematic uncertainties and limited MC statistics.

Process	ee	$\mu\mu$
DY	0.89 ± 0.21	0.54 ± 0.16
$t\bar{t}$	<0.01	<0.01
Diboson	0.075 ± 0.005	0.059 ± 0.010
Multijet/W + jets	0.16 ± 0.20	...
Total background	1.13 ± 0.29	0.60 ± 0.16
$M_S = 1.5$ TeV	72 ± 5	47 ± 9
$M_S = 2.0$ TeV	40.2 ± 2.6	22 ± 4
$M_S = 2.5$ TeV	11.7 ± 0.9	6.3 ± 1.1
$M_S = 3.0$ TeV	4.2 ± 0.4	2.3 ± 0.4
Data	2	0

TABLE VI. Expected and observed 95% C.L. lower limits on M_S in the dielectron and dimuon channels, as well as for the combination of those channels without and with the diphoton channel in the GRW formalism. Separate results are provided for the different choices of flat priors: $1/M_S^4$ and $1/M_S^8$.

Channel	Prior	Expected limit (TeV)	Observed limit (TeV)
ee	$1/M_S^4$	2.88	2.73
	$1/M_S^8$	2.72	2.62
$\mu\mu$	$1/M_S^4$	2.83	2.83
	$1/M_S^8$	2.61	2.61
$ee + \mu\mu$	$1/M_S^4$	3.16	3.00
	$1/M_S^8$	2.96	2.85
$ee + \mu\mu + \gamma\gamma$	$1/M_S^4$	3.43	3.22
	$1/M_S^8$	3.27	3.12

TABLE VII. Observed 95% C.L. lower limits on M_S (in units of TeV), including systematic uncertainties, for ADD signal in the GRW, Hewett and HLZ formalisms with no K factor applied to the signal. Separate results are provided for the different choices of flat priors: $1/M_S^4$ and $1/M_S^8$.

Channel	Prior	GRW	Hewett	HLZ				
				$n = 3$	$n = 4$	$n = 5$	$n = 6$	$n = 7$
ee	$1/M_S^4$	2.73	2.44	3.25	2.73	2.47	2.30	2.17
	$1/M_S^8$	2.62	2.48	2.86	2.62	2.49	2.40	2.34
$\mu\mu$	$1/M_S^4$	2.83	2.52	3.36	2.83	2.55	2.38	2.25
	$1/M_S^8$	2.61	2.47	2.85	2.61	2.48	2.40	2.33
$ee + \mu\mu$	$1/M_S^4$	3.00	2.68	3.57	3.00	2.71	2.52	2.39
	$1/M_S^8$	2.85	2.70	3.11	2.85	2.71	2.62	2.54
$ee + \mu\mu + \gamma\gamma$	$1/M_S^4$	3.22	2.88	3.83	3.22	2.91	2.71	2.56
	$1/M_S^8$	3.12	2.95	3.40	3.12	2.96	2.86	2.78

TABLE VIII. Observed 95% C.L. lower limits on M_S (in units of TeV), including systematic uncertainties, for ADD signal in the GRW, Hewett and HLZ formalisms with K factors of 1.6 and 1.7 applied to the signal for the dilepton and diphoton channels, respectively. Separate results are provided for the different choices of flat priors: $1/M_S^4$ and $1/M_S^8$.

Channel	Prior	GRW	Hewett	HLZ				
				$n = 3$	$n = 4$	$n = 5$	$n = 6$	$n = 7$
ee	$1/M_S^4$	2.95	2.63	3.51	2.95	2.66	2.48	2.34
	$1/M_S^8$	2.82	2.67	3.08	2.82	2.68	2.59	2.52
$\mu\mu$	$1/M_S^4$	3.07	2.74	3.65	3.07	2.77	2.58	2.44
	$1/M_S^8$	2.82	2.67	3.08	2.82	2.68	2.59	2.52
$ee + \mu\mu$	$1/M_S^4$	3.27	2.92	3.88	3.27	2.95	2.75	2.60
	$1/M_S^8$	3.09	2.92	3.37	3.09	2.94	2.84	2.76
$ee + \mu\mu + \gamma\gamma$	$1/M_S^4$	3.51	3.14	4.18	3.51	3.17	2.95	2.79
	$1/M_S^8$	3.39	3.20	3.69	3.39	3.22	3.11	3.02

The limits obtained using the GRW formalism have been translated into the Hewett and HLZ formalisms using Eq. (4) with results shown in Table VII. Limits are also obtained with a K factor applied to the ADD signal yield to account for next-to-leading-order QCD corrections. A constant K

factor of 1.6 is applied in the dilepton channel [62] and 1.7 in the diphoton channel [63]. The dilepton-diphoton combination increases limits by approximately 0.2 (0.3) TeV with a prior flat in $1/M_S^4$ ($1/M_S^8$), taking QCD corrections into account as shown in Table VIII.

IX. CONCLUSIONS

A search for contact interactions and large extra dimensions has been performed in dielectron and dimuon events produced in LHC proton-proton collisions at $\sqrt{s} = 7$ TeV. The data sample corresponds to an integrated luminosity of 4.9 (5.0) fb^{-1} of pp collisions in the dielectron (dimuon) channel recorded with the ATLAS detector. No significant deviation from the Standard Model is observed in the dilepton mass distributions. Using a Bayesian approach with a prior flat in $1/\Lambda^2$, as was done in most previous searches at hadron colliders, the following 95% C.L. limits are set on the energy scale of contact interactions: $\Lambda^- > 12.1$ TeV ($\Lambda^+ > 9.5$ TeV) in the dielectron channel and $\Lambda^- > 12.9$ TeV ($\Lambda^+ > 9.6$ TeV) in the dimuon channel for constructive (destructive) interference in the left-left isoscalar compositeness model. Somewhat weaker limits are obtained with a prior flat in $1/\Lambda^4$. These limits improve existing bounds on $eeqq$ and $\mu\mu qq$ contact interactions from a single experiment. Limits are also set on the scale M_S in the ADD large extra dimensions model. Those range from 2.4 to 3.9 TeV depending on the choice of model, channel, and prior. After combining the dilepton and diphoton searches, the limits are in the range from 2.6 to 4.2 TeV.

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